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Seismic stability of soil nailed excavations

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ABSTRACT: Dynamic centrifuge tests were conducted on soil nailed excavation models to investigate the stability and failure mechanisms under earthquake loading. The centrifuge test results showed excellent stability under seismic loading for soil nailed structures built according to general specifications and common practice adopted in California. The experiments revealed a consistent failure mechanism, consisting of a composite unit of soil and nails moving as a semi-rigid block, behind which an active earth pressure wedge developed. The measured inclinations of the active earth pressure wedge are also compared with predicted inclination angles calculated from the equilibrium of forces using a pseudostatic method of analysis. The nails' length and rigidity varied from test to test. The results show that the nail length strongly influenced the stability, but did not affect the failure mechanism. The rigidity of the model nails neither influenced the stability nor the failure mechanism.

INTRODUCTION

Soil nailing is a method of stabilizing vertical excavations and steep slopes with passive inclusions. The inclusions, commonly called nails, are installed *in-situ* as the excavation proceeds. Accordingly, unlike reinforced earth walls, soil nailing utilizes a "top down" construction procedure. The soil nailing concept is to reinforce the soil with these inclusions so that the nailed soil mass behaves as a composite unit, similar to a gravity retaining wall supporting a soil backfill (Juran and Elias, 1991; Mitchell and Villet, 1987).

Grouted nails are the most common type used in California. Typical horizontal and vertical nail spacings of grouted nails range between 1 m to 3 m, depending upon the soil conditions and geometry restrictions. The nails are able to resist tensile forces, shear forces, and bending moments. Immediately after the installation of a row of nails, the soil surface is covered by a facing. The most common type is a 100 mm to 250 mm thick shotcrete facing reinforced with welded wire mesh. Vertical excavations of up to 21 m have been successfully shored with grouted nails (ENR, 1991).

A typical cross section of a completed soil nailed structure with grouted nails is shown in Figure 1. This soil nailed structure, constructed in San Ramon, California, was subjected to seismic shaking during the 1989 Loma Prieta Earthquake along with seven other similar soil nailed structures. These structures did not show any visible movements or other signs of distress, even though they experienced horizontal ground accelerations probably as high as 0.4 g (Felio et al. 1990). Such excellent performance and stability of soil nailed structures during earthquakes has been confirmed by the writers on the basis of dynamic centrifuge test results (Tufenkjian et al., 1991). Some aspects of these centrifuge test results are discussed herein.

CURRENT DESIGN PROCEDURES

Most of the current design methods for soil

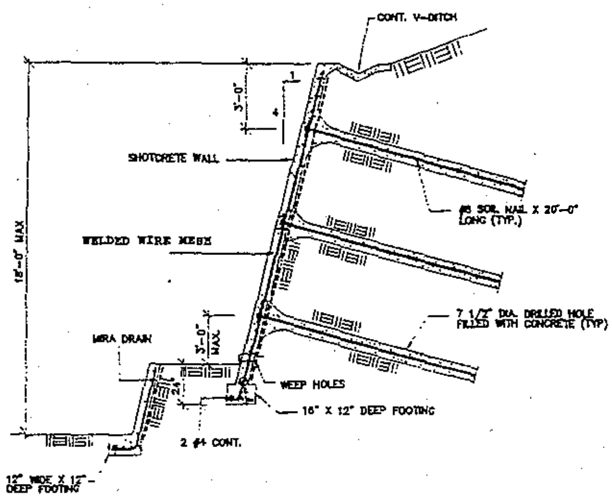

Figure 1. Cross section of a typical soil nailed structure, San Ramon, California, (after Barar, 1990).

nailed retaining structures under static loads are derived from classical slope stability analyses. These methods of analyses evaluate global factors of safety along assumed failure surfaces. Presently, soil nailing design methods do not explicitly incorporate seismic effects. A few investigators have extended current limit equilibrium design procedures to incorporate seismic forces (e.g. Barar, 1990). Their approach simulates seismic forces by using an equivalent static horizontal force applied at the center of gravity of the potentially unstable soil nailed mass. This pseudostatic approach is identical to what is used in the seismic analysis of reinforced earth walls (Mitchell and Christopher, 1990). As an alternative, a dynamic analysis employing a finite element code may be used to investigate the seismic stability at a more "realistic" level (e.g. Segrestin and Bastick, 1988).

A lack of full scale observations on failure mechanisms has led to different points of view about the correct methods of analyses for static and seismic stability. This investigation was undertaken to cast more light on possible modes of failure under dynamic loading conditions.

CENTRIFUGE TESTING

To recreate in-situ failure conditions, a geotechnical centrifuge was used. The failure mechanism and dynamic stability were assessed by varying either the model nail length or model nail rigidity in each test. Previous centrifuge investigations of soil nailed models include static tests performed by Shen et al. (1981), and static tests conducted as a part of the French Clouterre project (Plumelle et al., 1990; Schlosser, 1989). However, to the writers' knowledge, this is the first time that dynamic centrifuge tests have been performed to assess the seismic stability of soil nailed excavations.

The centrifuge tests were performed at the Rensselaer Polytechnic Institute (RPI) Geotechnical Centrifuge Research Center on a 3m radius Accutronic 665-1 centrifuge (Elgamal et al., 1991). The scale factor was selected to be 50 in all of the tests. Accordingly, to simulate prototype stresses, the models has to undergo a centrifugal acceleration of 50 g's. For dynamic testing, a servo-hydraulic earthquake simulation shaker mounted on the centrifuge platform was used. Five models were tested. Four models represented a 7.6 m high soil nailed excavation with grouted nails, while one model represented the same excavation height, but without nails. The soil nailed models roughly corresponded to an excavation height of a two to three story underground garage.

The effects of two important characteristics of soil nailed structures were tested: (1) the length of nails, expressed in terms of the "length ratio," defined as the ratio between the nail length and the excavation height, H; and (2) the axial and flexural rigiditics of the nails. Table 1 summarizes the testing program. Tests 2 and 4 had a nail length ratio of 0.67, i.e. within the nail length ratio range of 0.5 to 0.8 most commonly used in practice (Bruce and Jewell, 1987). The San Francisco Bay area soil nailed structures subjected to seismic shaking during the 1989 Loma Prieta earthquake also had length ratios within this range, or sometimes larger. The nail lengths in Test 1 were shorter than typical, corresponding to a length ratio of 0.33, while in Test 3 they were longer, with a length ratio of 1.0. The model nails in Tests 1, 2 and 3 were fabricated from the same material, and were scaled to approximately correspond to prototype axial and flexural rigidi-

Table 1. Summary of Centrifuge Testing Program

Test No.	Length of Nails		Rigidity of Nails	
	Length	Length Ratio	Axial	Flexural
-	L	$\frac{L}{H}$	$(EA)_m$	$(EI)_m$
0	Reference test without nails; soil failed during spin-up			
1	Short	0.33	Regular	Regular
2	Medium	0.67	Regular	Regular
3	Long	1.00	Regular	Regular
4	Medium	0.67	Small	Small

E = Young's Modulus of Elasticity
A = Cross Sectional Area
I = Moment of Inertia
m = Subscript denoting "model"

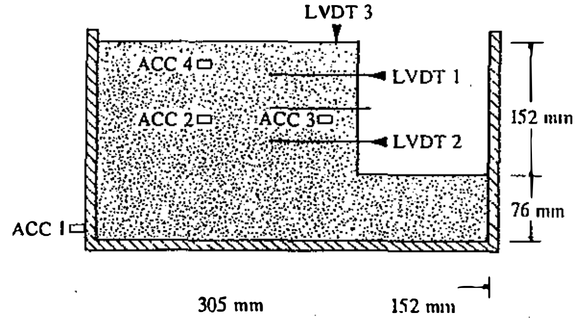

Figure 2. Location of instrumentation and dimensions of soil nailed excavation model.

ties. However, the nails in Test 4 were fabricated from a material which had small axial and flexural rigidities compared to the nail rigidities used in Tests 1, 2 and 3. By varying the axial and flexural rigidities of the soil nails, their effect on the failure surface geometry and stability could be assessed.

Three LVDT-s were used to record the lateral movements of the facing, and the vertical soil settlement behind the facing. During dynamic loading, four accelerometers were utilized to measure accelerations in various locations within the model box. Figure 2 shows the dimensions and the instrument locations of a soil nailed excavation model.

The soil used in the experiments was Silica Sand #120, manufactured by US Silica, with a grain size ranging between 0.05 mm and 0.30 mm. Partially saturated soil was used to give the sand an apparent cohesion, which can roughly simulate in-situ cohesion and cementation. Soil nailing is most effectively utilized in cohesive or cemented soils, which facilitates field construction of the temporarily unsupported vertical excavation steps.

TEST RESULTS

Each test was performed in two stages. First, to replicate in-situ stress conditions, the soil nailed excavation models were spun up to 50 g's centrifugal acceleration. The recorded facing movements that occurred during the spin-up were comparable to corresponding field measurements on soil nailed retaining structures reported in the literature (Bruce and Jewell, 1987; Tufenkjian et al. 1991). Such agreement between the centrifuge model behavior and field behavior indicates the centrifuge's ability to simulate the in-situ static conditions.

In the second stage of the test, one directional horizontal shaking of the model box was performed by the on-board earthquake simulation shaker. During this stage the dynamic stability, the shape of failure surfaces, and failure mechanism were observed. In each test, the horizontal shaking included one to ten events of ten constant amplitude sinusoidal acceleration cycles. These dynamic loading events were applied at 100 Hz, which correspond to a prototype frequency of 2 Hz. The models were first subjected to a prototype acceleration time history of ten cycles with an amplitude of 0.1 g. These were followed by the same sinusoidal time histories, but with the prototype acceleration amplitudes scaled upward, until a complete failure of the soil nailed excavation was observed through the video monitoring system. The complete failure was arbitrarily defined as the occurrence of large deformations and clearly visible failure surfaces.

Figure 3 shows the failure mechanisms of Tests 1, 2, 3 and 4. In each case, the failure occurred along two failure surfaces. One fail-

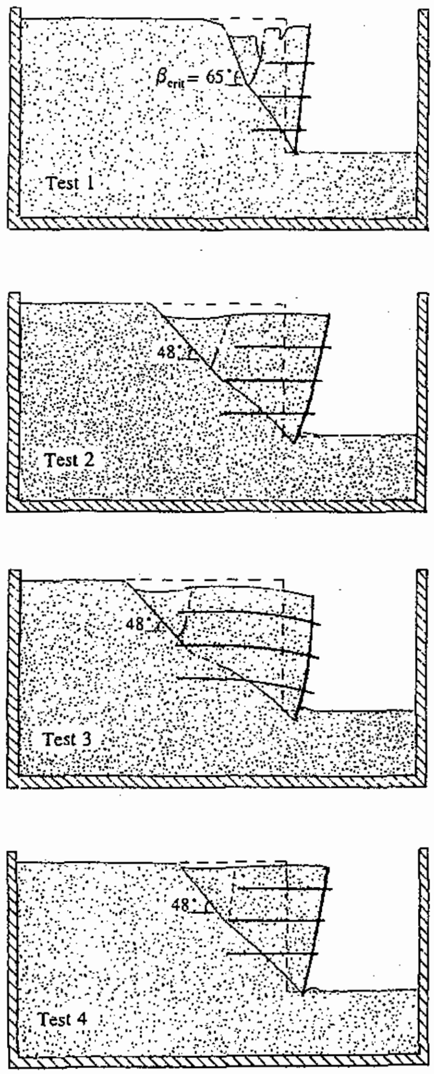

Figure 3. Observed modes of failure.

ure surface extends from behind the nails at the ground surface down to the end of the second row of nails, while the other is continuing from the end of the nails in the second row down to the bottom of the excavation through the toe. The upper surface is practically straight, while the lower one is always slightly concave downwards. As shown in Figure 3, there exists a third failure surface within the moving soil mass, which extends vertically down from the ground surface to nearly the second row of nails. This failure surface is readily apparent in Test 1, but not as obvious in Tests 2, 3 and 4. Note that this failure surface moves back as the length of nails increases. A more detailed preliminary explanation of the associated failure mechanism can be found elsewhere (Tufenkjian et al., 1991).

The wedge of soil located behind the top two rows of nails is apparently analogous to the active earth pressure wedge that develops behind retaining walls. In this case, the retaining wall can be considered the composite unit of soil and nails bounded by the earth pressure wedge to the left and the lower failure surface.

The measured inclination of the active failure wedge, β_{crit}, varied with the magnitude of applied acceleration at the base of the model as indicated in Figures 3 and 4. Also plotted in Figure 4 are two curves computed from the trial wedge method using a planar failure surface. The assumed forces acting on the trial wedge are shown on the insert in Figure 4. The method considers a horizontal inertia force which is equal to the weight of the soil wedge multiplied by a horizontal acceleration coefficient. A similar vertical inertial force was not considered. To find β_{crit}, the values of β were varied until the maximum value of R was found, which corresponds to the minimum active earth pressure.

The upper curve in Figure 4 represents cohesion and friction angle values of 7.2 kN/m^2 and 36° respectively, which were calculated from direct shear tests on the model sand. As a comparison, the lower curve was computed by keeping the friction angle constant at 36° and setting the cohesion equal to zero. Figure 4 shows a consistent trend between the calculated and measured β_{crit} angles. However, the calculated angles are consistently smaller than the corresponding measured angles. Similar curves have been derived by Davies et al. (1986) by solving the Mononobe-Okabe equations for various angles of wall friction. However, unlike the analysis by Davies et al., the analysis presented in Figure 4 also accounted for soil cohesion as a part of the force equilibrium.

The flattening of the β_{crit} angle from the static condition ($k_h = 0$) with increasing acceleration levels ($k_h > 0$) is consistent with analytical and experimental results provided in the literature (e.g. Davies et. al., 1986; Elms and Richards, 1990; Murphy, 1960). According to Figure 3, the measured inclination of the failure

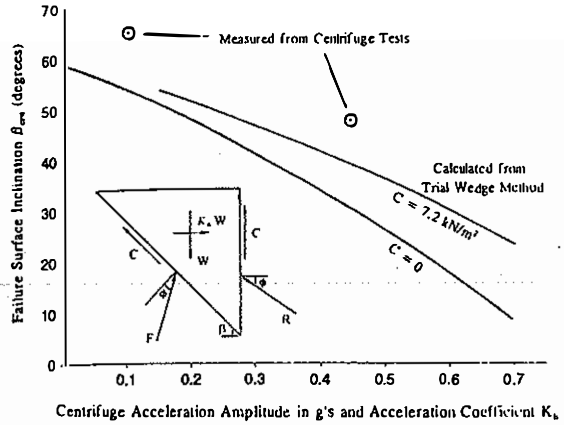

Figure 4. Effect of measured and calculated acceleration levels on the failure surface inclination.

surface, β_{crit}, remained constant for Tests 2, 3 and 4, despite having different nail lengths and rigidities. The unique common feature of Tests 2, 3 and 4, was the magnitude of maximum acceleration level of 0.45 g which produced the failure surfaces, while in Test 1 the maximum acceleration was 0.1 g.

This is also shown in Table 2, which compares the failure conditions of Tests 1, 2, 3 and 4. Test 1, with a length ratio of 0.33, failed after the input of only one "seismic event." On the other hand, Test 3, with a length ratio of 1.0, required the input of ten "seismic events" to develop the failure surfaces, with the acceleration magnitude of the last eight events equal to 0.45 g. In Tests 2 and 4, where the length ratios were the same but the nail rigidities were different, the results were comparable.

The difference in stability between Tests 1 thru 4 can be attributed to the different nail lengths used in each test. In Test 1, the instability occurred due to the small volume of nail reinforced soil, i.e. the correspondingly small frictional resistance along the lower failure surface and bottom row of nails beyond the failure surface. In Test's 2, 3 and 4, which had length ratios of 0.67 and 1.0 respectively, much larger frictional resistance developed along the lower failure surface and the bottom row of nails beyond the failure surface, because of the larger nail lengths involved. It is apparent that the bottom row of nails beyond the failure surface behaved as anchors between the failed sliding soil mass and the soil behind it, while the top two rows of nails held the soil together in the upper part of the excavation.

Table 2. Summary of failure conditions

Test No.	Length Ratio	No. of "Seismic" Events to Failure (Each Event = 10 cycles)	Level of Horizontal Shaking at Failure	β_{crit}
1	0.33	1 $1\times0.1g$	0.1g	65°
2	0.67	4 $\begin{cases}1\times0.1g\\1\times0.27g\\2\times0.45g\end{cases}$	0.45g	48°
3	1.0	10 $\begin{cases}1\times0.1g\\1\times0.27g\\8\times0.45g\end{cases}$	0.45g	48°
4	0.67	3 $\begin{cases}1\times0.1g\\1\times0.25g\\1\times0.45g\end{cases}$	0.45g	48°

The 0.1g seismic event experienced by the soil nailed structure in Test 1 may be equivalent to a moderate to strong earthquake in the field. But, the consecutive cycles of 0.45g amplitude accelerations experienced by the models in Tests 2, 3 and 4, are events of extreme ground shaking, which in reality are not possible. Therefore, it can be concluded that soil nailed structures with grouted nails should resist large earthquakes. Indeed, eight such soil nailed structures, subjected to maximum horizontal accelerations between 0.1g and 0.4g during the 1989 Loma Prieta earthquake in the San Francisco Bay area, behaved very well and did not show any signs of excessive deformation (Felio et al., 1990).

CONCLUSIONS

A series of dynamic centrifuge tests was conducted on soil nailed excavation models to investigate the stability and failure mechanism under earthquake loading. The dynamic tests showed excellent stability of typically constructed soil nailed retaining structures by withstanding large if possible seismic events. The test results showed that the failure mechanism consisted of a composite unit of soil and nails moving as a semi-rigid block, behind which an active earth pressure wedge developed. The measured inclination of this failure wedge showed a consistent trend with calculated failure angles computed from the trial wedge method. The measured inclination of the wedge decreased for larger amplitudes of cyclic acceleration applied at the base of the models. The stability of the soil nailed models was shown to be mainly a function of the nail length and strength, while a decrease in nail axial and flexural rigidity did not play a significant role.

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